Effects of Offshore Forcing in the Nearshore Environment

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LONG-TERM GOALS

The broad objective of the project is to extend our understanding on the role of offshore baroclinic forcing in nearshore dynamics. From this understanding we aim to develop modeling approaches that, combined with offshore baroclinic models, can account for the effects of offshore internal wave forcing on the circulation and sediment transport in the coastal zone.

OBJECTIVES

Specifically, the work aims to address two questions:

1. How is offshore baroclinic tidal energy manifested in the nearshore environment, i.e.what is the transfer function between internal tides and nearshore currents?

2. What is the role of baroclinic tidal energy in nearshore circulation and, subsequently, on sediment transport? The work focuses on real-time observations combined with event-driven sampling methodology to highlight the role of offshore tidal and wave forcing in the circulation and transport dynamics in the nearshore. Important secondary objectives include validation of the Delft3D model in capturing the effects of baroclinic forcing and predicting hydrodynamic circulation and sediment transport in the spatially complex environment posed by a carbonate reef.

APPROACH

Field observations examining the nearshore response to offshore forcing are being carried out on the south shore of Oahu, focusing on the Kilo Nalu Observatory (www.soest.hawaii.edu/OE/KiloNalu/) (Figure 1). The field work is being carried out in parallel with development of a nested, high-resolution numerical model for the study region.

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The observatory presently includes cabled nodes at 10 and 20 m depths (~0.4, 0.8 km from the shoreline, respectively). The existing cabled instrument array includes ADCPs and thermistor chain moorings at each node and a near-bed turbulence microprofiler and basic water property measurements (T, S, DO, Chl, turbidity) at the 10m site. The ONR funded work is supporting development and deployment of a string of bottom-mounted temperature and pressure sensors extending to 100 m depth that will enable measurement of baroclinic energy fluxes across the shelf. A series of focused field observations were carried out in summer 2007 using cabled and autonomous instrumentation (figure 1) combined with AUV based spatial sampling. An offshore deep water profiling mooring was deployed between June and November 2007 in collaboration with Matthew Alford (UW APL) although this provided limited data due to a profiler failure.

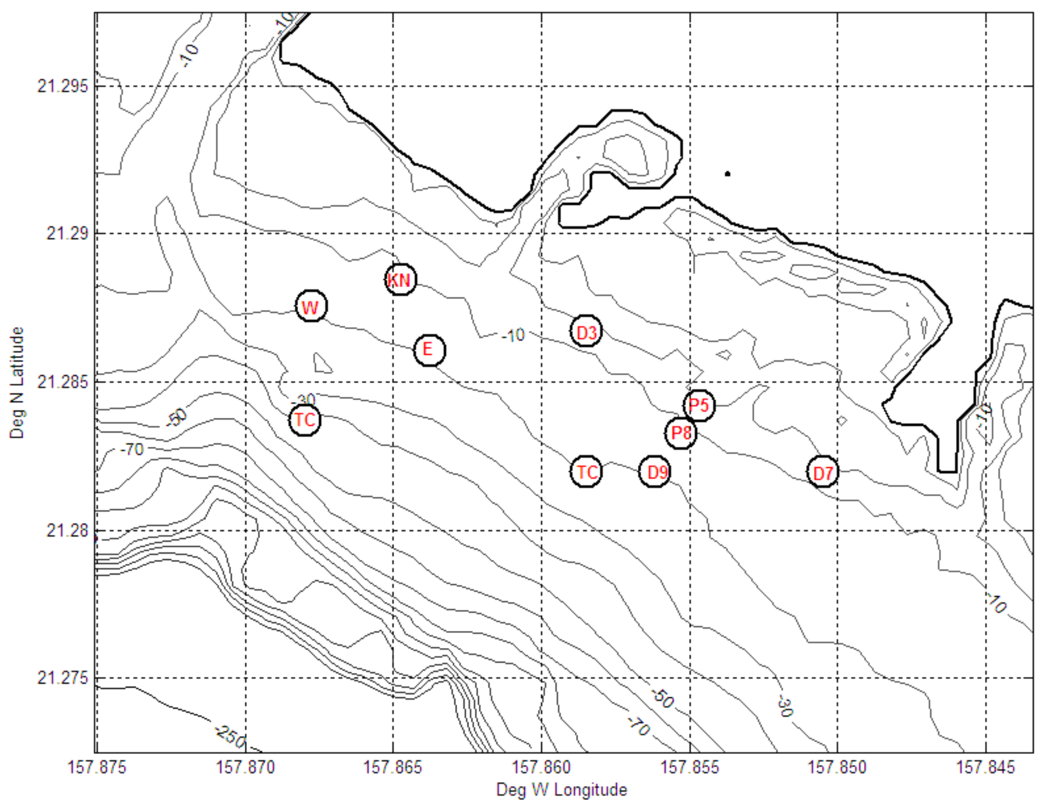

Figure 1 – Summer 2007 field instrumentation array. Kilo Nalu cabled array (KN) is at upper left. P5, P6: Aquadopp PUV current profiler; D3, D7, D9: Aquadopp PUV current meter; E, W: ADCP current profiler; TC: T-chain.

A nested modeling approach is under development to resolve the nearshore internal tide. A 1 km Princeton Ocean Model (POM) run spanning the Molokai Channel has been completed that captures the main features of the offshore internal tide as it propagates westward from the primary generation site on the east side of the channel. We are presently developing a nested, higher-resolution (20m) inner-shelf model using Delft3D with which we will specify the internal tide at the Kilo Nalu test site.

As an extension to the focus on offshore forcing effects in the nearshore and as a follow-on to earlier funded ONR work (N00014-03-1-0486), we have also been carrying out analysis of field data examining dynamics of wave-driven flow over irregular roughness. These observations make use of

novel profiling techniques that enable spatial resolution of the wave boundary layer structure over a 2 m stretch of reef.

Two postdoctoral researchers Judith Wells and Jeremy Bricker, and two graduate students, Marion Bandet and Greg Rocheleau, have been supported in part by this ONR project. The project is also providing partial support for a research technician, Kimball Millikan, who has participated in field operations and experiment design.

WORK COMPLETED

The initial stages of the project focused on development of the broader scale model components, collection of field observations, along with statistical analysis of earlier time series data from Kilo Nalu. More recently, work has focused on analysis of the extensive set of observations carried out in summer 2007, targeted at resolving the region extending from the surf zone to offshore depths. Modeling efforts have pursued development of the nearshore model component. Development of a three-dimensional model capable of accurately reproducing baroclinic flow using the DELFT3D platform has highlighted a number of challenges. In particular, the boundary conditions on flow and stratification introduce significant constraints that can lead to spurious results if not dealt with carefully.

Statistical analysis of the multi-year Kilo Nalu 10m temperature record has shown that temperature cooling ‘events’ associated with shoaling internal tides are pervasive, occurring across tidal phases, current directions and seasons even though they follow periodic patterns. AUV surveys, carried out in November 2006, targeted resolution of the alongshore baroclinic structure and identified high alongshore spatial variability in stratification indicating that boundary condition between the large scale and the nearshore model will require spatial data. Analysis of further AUV survey data from July 2007, combined with cabled and autonomous data, was able to establish a link between shoaling baroclinic energy from offshore and high frequency nearshore currents.

The Kilo Nalu 10m data set has also highlighted a significant stochastic residual component in the currents extending over a broad spectral range. Variability in the currents is dominated by the M2 frequency which accounts for roughly 35% of the total variance. Higher frequencies including M4 and M6 also have significant contributions to the velocity field. One of the key objectives for the work is to establish the mechanisms that drive this variability in order to achieve accurate and predictive modeling.

Regression fits to the M2 component of the 10m alongshore velocity at Kilo Nalu using the surface tidal signal from Honolulu Harbor have been used to isolate periods of high variability that are not coherent with the surface tide. We can loosely interpret the surface tidal signal as an analog for the barotropic tide. The regressed tidal signal and observed M2 component show periods of close agreement, along with significant periods where there is a strong M2 component that is not accounted for by the surface signal. The working hypothesis has been that this residual variance is related to the velocity field associated with strong offshore baroclinic motions. The objective of the summer 2007 array (figures 1, 2) was to examine this relation, resolving the offshore baroclinic structure along with its nearshore manifestation.

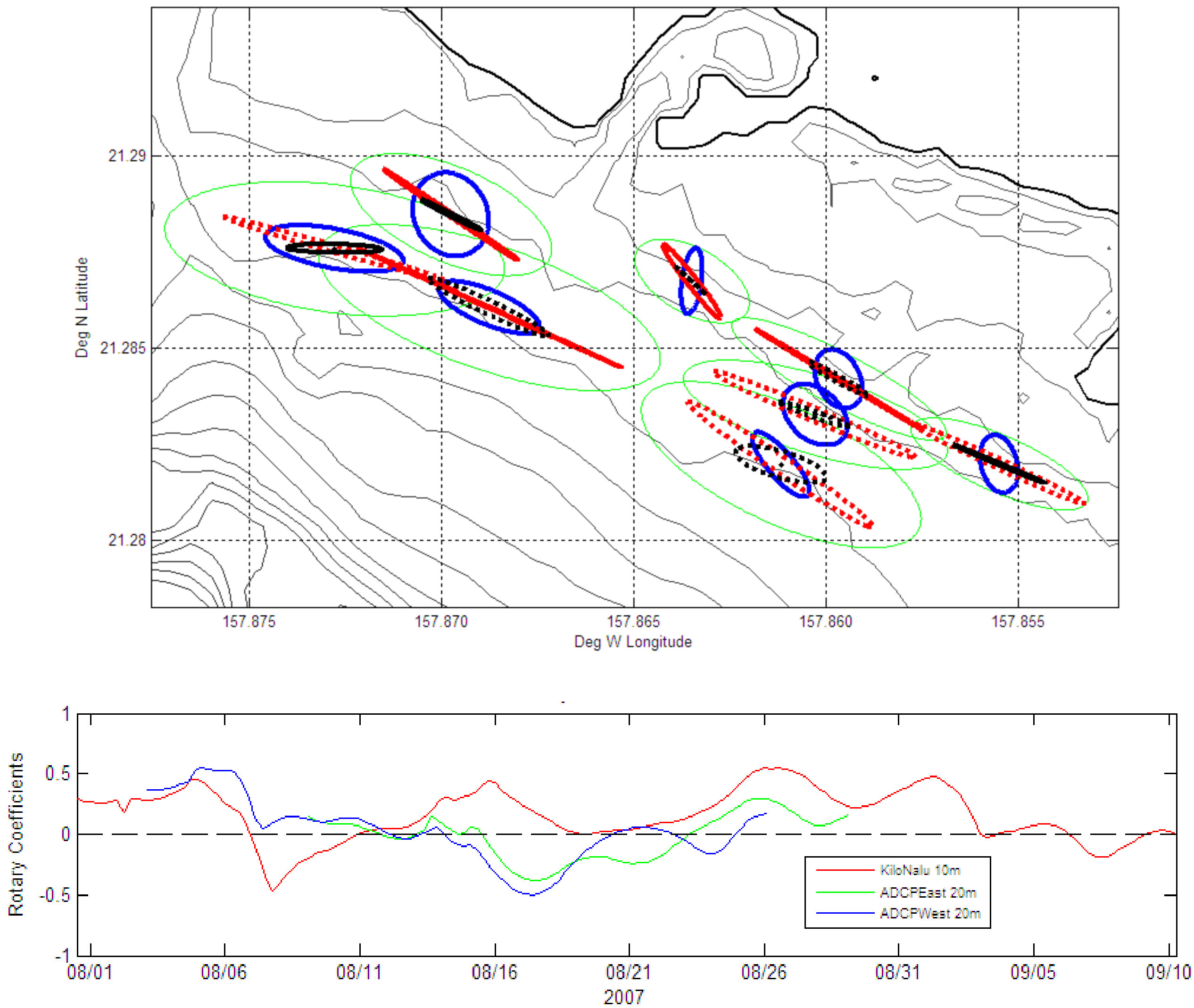

Figure 2 – A) Current ellipses at observational array locations. Green ellipses show current ellipses including all frequencies (>1 hr period). Blue: Diurnal band; Red: Semi-diurnal band; Black: M4 band. CCW rotation is indicated by solid lines, CW by dotted lines. B) M2 band rotary coefficients (+CCW, -CW) for KN, ADCP-W and ADCP-E sites, illustrating temporal variability in rotational flow structure.

Due to failure of the offshore profiling mooring, data was limited to temperature/pressure records from the top and bottom of the mooring. The deep temperature fluctuations, which can represent vertical displacements of tens to hundreds of meters, were used as an surrogate for baroclinic forcing. Regression analyses of the temperature record, following that described above for the alongshore currents have not revealed clear connections, however, between periods of high or low unexplained variance. This suggests either that the significant unexplained variance at M2 (and other frequencies) is not associated with internal tide activity, or that the association is more complex than anticipated. Previous studies of the internal tide in Mamala Bay have indeed revealed complex spatial and temporal structure (Eich et al 2004, Alford et al 2006). This variable structure may complicate the offshore

temperature time series due to baroclinic energy propagating in both alongshore directions, for example.

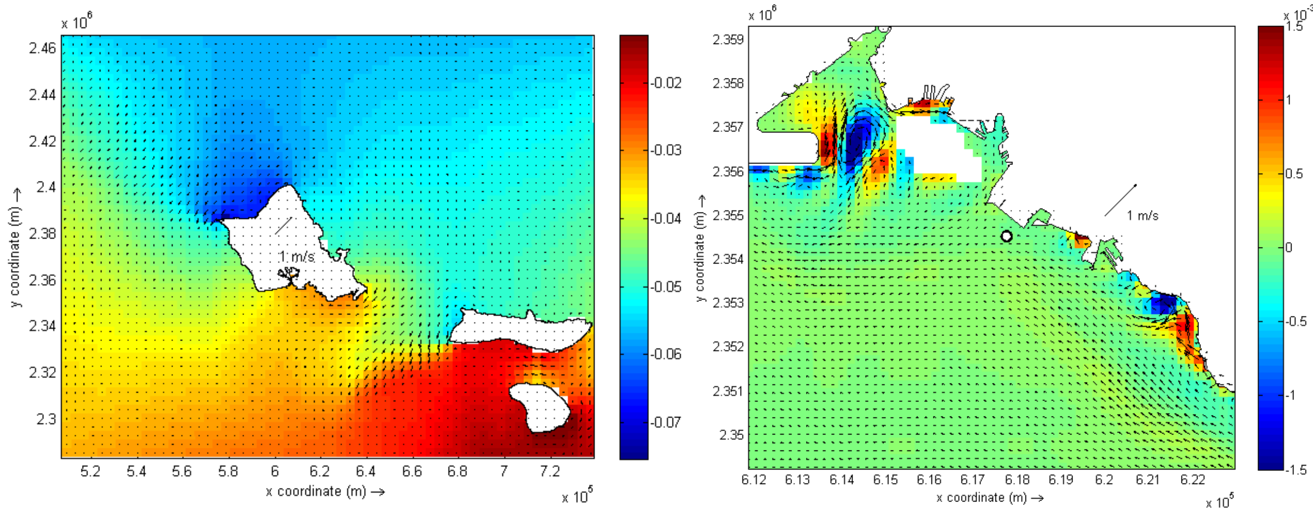

Figure 3 – Left: outer grid solution for surface height (color: m) with velocity vectors overlaid. Coarse grid model is forced with 8 tidal constituents. Right: High resolution model barotropic solution for vorticity (color: s^{-1}) with velocity overlaid, for Kilo Nalu vicinity (Kilo Nalu location indicated by circle). Fine grid model includes 1m, 15sec wave forcing representing background swell conditions. Image shows only a small subset of the high resolution model domain.

We are presently carrying out detailed analysis of the 2007 nearshore array that should shed further light on the flow structure across the spectral range. These data, along with extended time series from the 20m Kilo Nalu node should enable resolution of the nearshore structure associated with offshore baroclinic motions. Rotary spectral analysis of the array data has identified high spatial variability in flow structure across a range of tidal frequencies (figure 2). Rotational sense is seen to vary over short distances, suggesting that changes in locally generated vorticity may play important roles in flow structure. The rotational sense (figure 2, bottom) also varies considerably with time at the M2 frequency and others. This variability requires further analysis, but suggests that flow structure is likely non-linear and sensitive to offshore conditions and interactions in tidal frequencies.

Conclusive interpretation of the spatial structure will require a functional model capable of capturing the influence of offshore baroclinic motions as well as frictional interactions with the complex coastline and bathymetry. The regional internal tide has been described using the Princeton Ocean Model with 1km horizontal grid resolution and 61 sigma levels (figure 3). Runs have been made for the dominant semi-diurnal and diurnal constituents using TPXO6 to prescribe the barotropic forcing at the POM grid boundaries. The POM results are then used to force Delft3D. We have tried a number of grid configurations and boundary conditions to try and simulate the tide within the Delft3D grid domain. Our first approach is to use traditional nesting with downsizing from a course outer grid (1-2 km horizontal resolution), to an intermediate resolution middle grid (200m resolution), to a high resolution inner grid (10m resolution). When the outer grid is forced by POM water levels at the lateral boundaries and a homogeneous water column is invoked, we can simulate the barotropic current successfully in all grids with little apparent noise transitioning from one grid to the next (figure 3). Adding a depth-dependent temperature profile, specified using nearby Hawaii Ocean Time series data,

leads to the generation of the internal tide within the coarse grid (the grid is chosen so as to encompass the main generation site in the region); however, the solution is unstable as model errors generated at the course grid boundaries quickly migrate into the mid and inner grids.

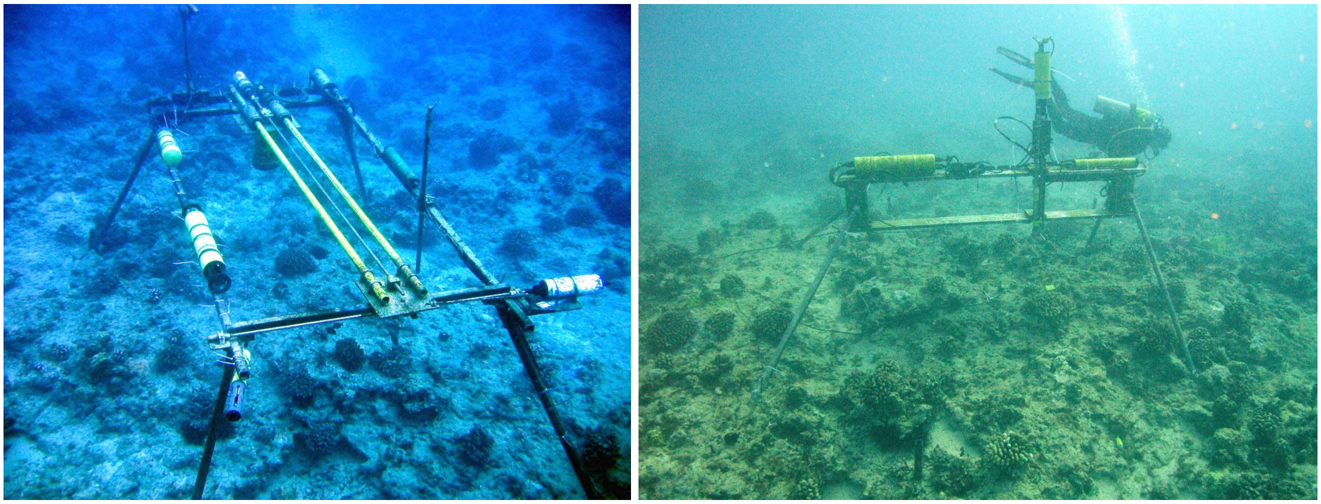

Figure 4: Left: Rough Boundary Profiler (RBP). The automated profiler moves instrument packages along a 3 m track (yellow bars) allowing resolution of the near-bed spatial structure. A shore cable connection provides real-time data and power. The instrument array pictured includes downward looking ADCP with upward ADV. Right: Kilo Nalu automated vertical profiler deployed over reef bed.

We have also tried a domain-decomposition in which two-way nesting is used for successively finer grids leading to the nearshore. A disadvantage with this approach is the need to generate a large number of nested domains in order to negotiate the abrupt transition from deep to shallow water over the steep slopes of Mamala Bay. This approach also is unable to provide a stable baroclinic tide solution using the simple boundary condition of surface elevation forcing at the outer domain.

The use of depth-dependent boundary conditions has been examined for the baroclinic runs, but these are very sensitive to mismatches in the specified boundary conditions, obtained from POM, and the radiated internal tide generated within the Delft3Ddomain. Mismatches are inevitable as the POM simulations do not capture all the detail of the internal tide generated within the higher spatial resolution Delft3D domains.

Our next series of model tests will involve the use of highly dissipative layers around the boundaries of the outer domain, or sponge layers, to absorb and dissipate the baroclinic tides generated within the domain. With our configuration of Delft3D, this can only be accomplished using the domain-decomposition grids. Our preliminary runs suggest that this is a promising approach, although more work is needed to diagnose growing model errors within the sponge layer itself. Our expectation is that this model configuration will be successful and that tests with baroclinic tides and ocean waves will commence by the end of 2008.

Analysis has also continued on extensive data sets collected as part of earlier ONR-funded work examining the near-bed structure of flow over highly rough bathymetry. The observations include data from deployments of the Rough Boundary Profiler (RBP; Figure 4L) which employs a downward

looking ADCP, profiling horizontally over a 2m stretch of reef. An automated vertical profiler was also deployed at Kilo Nalu over reef (Figure 4R) and sand beds to obtain high resolution vertical profiles of near-bed, wave-generated turbulence.

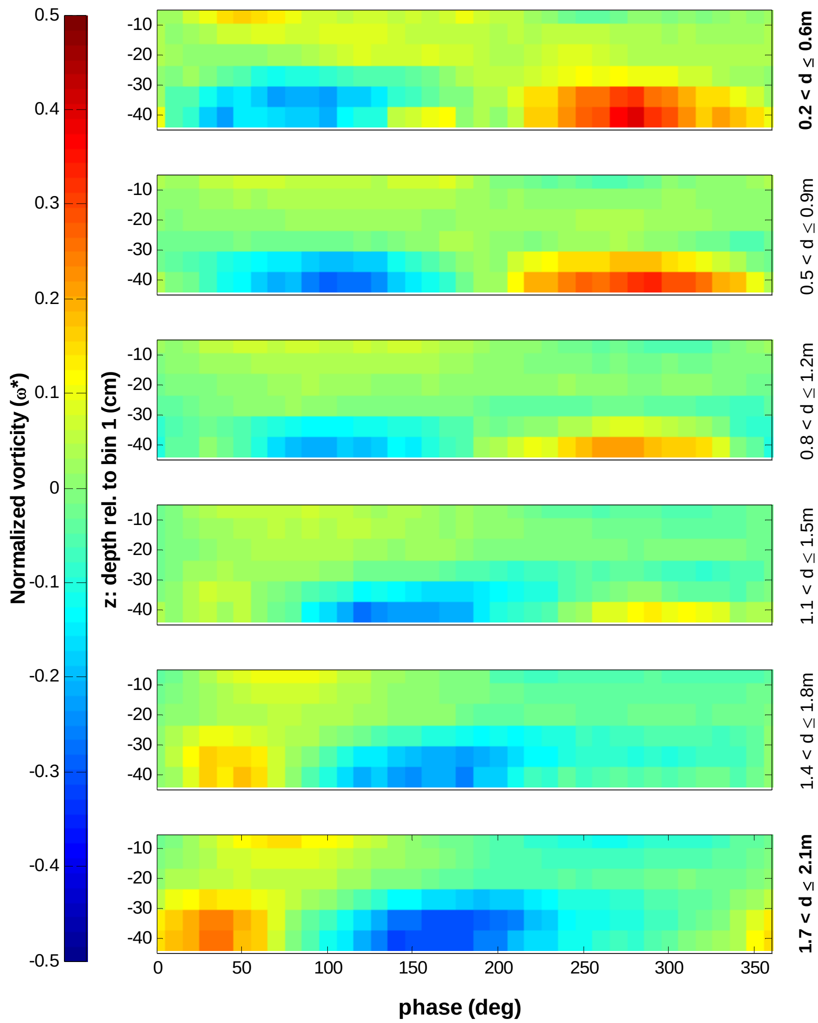

Figure 5 – Cross-shore averaged vorticity from RBP observations as a function of wave orbital amplitude. Vorticity is normalized by maximum wave velocity and an average dissipation height.

RBP data has been used to generate a two-dimensional, phase-averaged velocity field over a 2m (cross-shore) x 1m (vertical) plane, as a function of wave-orbital amplitude. Figure 5 shows the evolution of the normalized cross-shore-averaged vorticity as a function of wave phase for a range of orbital amplitudes. The data reveals a significant shift in phase for the near-bed vortical flow as the orbital amplitude changes. This shift, which has important implications for wave stress and dissipation, is associated with increased influence of larger bed roughness elements at as wave orbits increase. The structure is consistent with earlier observations of bed roughness (Nunes and Pawlak, 2008), also funded by ONR, which describe the reef environment by a red spectral roughness distribution.

Vertical profiler data taken at the same location over the reef has been used to obtain a profile of turbulent dissipation associated with near-bed wave-driven flow (figure 6). The observations reflect

highly energetic wave-driven turbulence with average dissipation rates consistent with wave dissipation factor of ~0.03-0.04. The dissipation height, δ_ε, defined as the height over which the integrated dissipation equals the average value, is consistent at about 23 cm across the range of wave conditions during the swell, suggesting that the boundary layer height for this very rough region is set by the local roughness scale. Our ongoing analysis of existing data, along with new data sets collected over sand, is exploring new methods for wave-turbulence decomposition which must be carried out to estimate Reynolds stresses in the near-bed region.

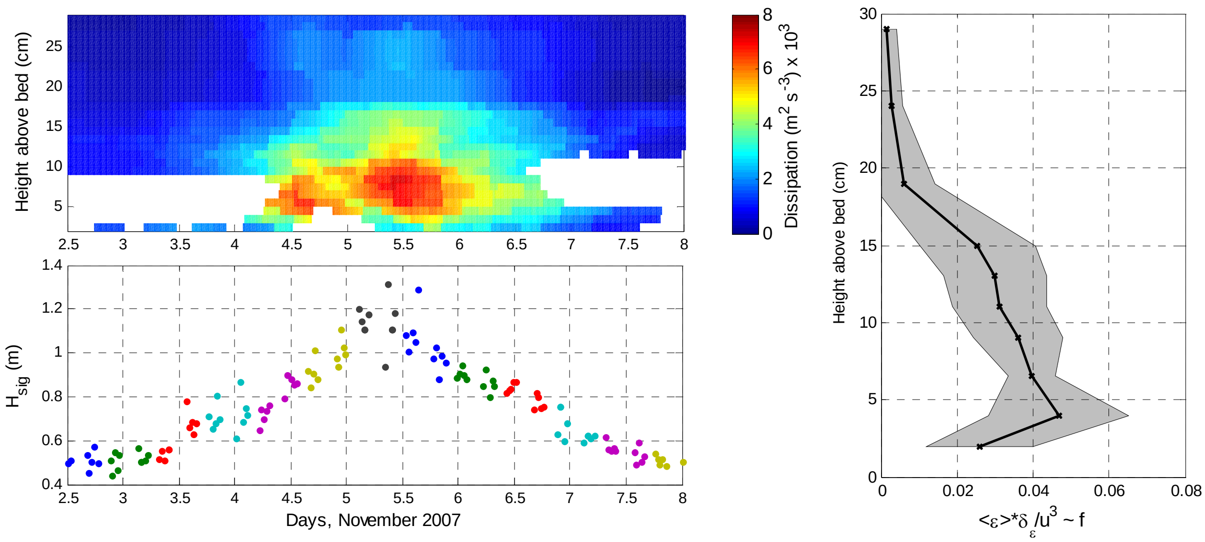

Figure 6 – Profiler observations of near-bed turbulent dissipation. Top left) Dissipation vs height, time over the course of a swell, highlighting wave-enhanced turbulence. Blank regions indicate low backscatter periods where near-bed effects impair measurements. Bottom left) wave height versus time. Each dot represents an individual data point with complete vertical profiles grouped by color. Right) Normalized dissipation vs. height for measurement period, indicating steady shape of dissipation profile.

IMPACT/APPLICATIONS

Understanding of the relation between internal tide dynamics and nearshore processes is critical for accurate modeling of currents and sediment transport.in the coastal zone. An important objective of the ongoing work is to provide a qualitative assessment of the DELFT 3D model as a tool for predicting circulation and sediment transport in the spatially complex island/reef coastline. The observations supported by this project have highlighted the complex relationship between offshore dynamics and currents in the nearshore zone. Effective modeling of waves, currents and sediment transport in the littoral zone of steep, complex coastlines will thus require accurate resolution of offshore baroclinic dynamics.

Work on dynamics of near-bed, wave driven flow has suggested a new paradigm for flow over very rough, inhomogeneous bathymetry, where a broad spectral roughness distribution leads to varying length scales as a function of wave-orbital diameter. These ideas are forming the foundations for new friction/dissipation parameterizations that are critical for modeling flow over complex boundaries.

The ongoing work is also supporting extension of the cabled Kilo Nalu Observatory baseline infrastructure. Kilo Nalu has enabled real-time access to data, facilitating deployment of instruments that would otherwise be limited to short-term deployments. The initial Kilo Nalu infrastructure was deployed largely with support of earlier ONR grant

RELATED PROJECTS

The work here is closely integrated with an NSF project, funded under the Coastal Ocean Processes (CoOP) program. The NSF work has funded an expansion of the Kilo Nalu Observatory including new baseline infrastructure. The work is examining the response of benthic boundary layer geochemical fluxes to physical forcing including surface waves and internal tides. The observations being undertaken as part of that work complement the broader scale field data collected for the ONR work. In particular, observations on small scale boundary layer processes will provide input to nearshore modeling using DELFT3D. Near-bed bistatic current Doppler velocimeter (BCDV) observations by Tim Stanton (NPS) can also provide data on sediment transport processes relevant to the ONR work. A comprehensive set of observations was initiated in July 2007 which coincided with the observations described earlier.

During the November 2006 experiment, two Kilo Nalu ADCPs serendipitously captured the signal associated with a small tsunami, generated by the November 15 Kuril Islands earthquake. Observations indicated that oscillations in pressure and velocity persisted for over two days. Analysis of the observations identified a significant component in the oscillations associated with coastal-trapped edge waves (Bricker et al, 2007).

The project is also benefiting from work carried out at Kilo Nalu via complementary projects. As part of the NSF CoOP project, a laser scanning altimeter (Tim Stanton, NPS) was deployed in Aug/Sept 2007. In addition, a sector scanning sonar collected data at the 10 m Kilo Nalu node in support of mine burial experiments (PIs R. Wilkens and M. Merrifield). AUV surveys carried out as part of this project and for the mine burial work are also obtaining sidescan imagery of the bedform morphology. ONR is also supporting development of AUV mapping resources for Kilo Nalu.

A newly funded NSF proposal will begin in 2009 (PI’s Monismith, Koseff, Pawlak, Nash), to examine the small scale turbulence associated with bores generated by shoaling internal tides. This work will complement and extend the broader scale observations supported by the project discussed above.

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